PERPENDICULAR-TO-GRAIN RHEOLOGICAL BEHAVIOR OF LOBLOLLY PINE IN PRESS DRYING

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ABSTRACT

To predict the thickness loss of loblolly pine lumber during press drying, a model was developed to describe the perpendicular-to-grain rheological behavior as a function of pressure, temperature, and drying time. The strain–time curve was divided into four parts—initial elastic deformation, viscoelastic deformation, final elastic springback, and time-dependent springback—according to the characteristic responses of these behaviors to pressure, temperature, and drying time. The model was fitted to experimental data by nonlinear regression. Good agreement was obtained between the predicted and experimental thickness loss during press drying.

Keywords: Drying, press drying, loblolly pine, southern pine, shrinkage, creep.

INTRODUCTION

Many studies have focused on hot press drying as a potential process for drying veneer and lumber. Recent research (Simpson et al. 1988) has shown that compared to kiln drying, press drying significantly reduces warp in fast-grown plantation loblolly pine and also reduces the drying time of 2 by 4 lumber to less than 2 h. Because of the pressure and high temperature employed in press drying, concerns have developed about how much thickness is lost and how to predict

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this loss. Excessive thickness loss decreases yield because larger green target thickness is necessary to meet dry thickness requirements. The study reported here was designed to characterize the rheological behavior of 2 by 4 loblolly pine lumber in compression perpendicular to the grain under various conditions of pressure, temperature, and drying time. The main objectives of the study were to develop a mathematical model to predict thickness loss in press drying and to better understand the rheological behavior of lumber during press drying.

BACKGROUND

The perpendicular-to-grain rheological properties of wood have been the subject of several studies (Kunesh 1961; Schniewind 1968; Wang 1985, 1987; Youngs 1957). The results show that wood creep behavior can be represented by linear viscoelastic theory under certain stress and strain conditions. However, when the temperature and moisture content change during loading, viscoelastic behavior becomes more complicated and difficult to characterize with practical mathematical functions.

The effect of constant temperature, stress, and moisture content on rheological properties of wood has been investigated (Bazant 1985; Schniewind 1968; Wang 1985; Youngs 1957). Ranta-Maunus (1975) studied the creep deformation of beams in bending with periodically cycled bending moment and moisture content. Two types of behavior were noted in this study. Some species continued to increase in strain with periodic variation in moisture content, whereas other species had no cumulative strain with variation in moisture content. Wang (1987) investigated the creep behavior of poplar as water vapor passed through the specimen. He observed that the elastic compliance and retarded elastic compliance increase only slightly with increasing temperature in the range of 20 C to 105 C in the oven-dry condition, but increase sharply with increasing temperature at higher moisture contents or with the passage of water vapor through the specimens. However, useful mathematical models to describe the rheological behavior of wood as a function of stress, temperature, and moisture content have not been developed. The many pieces of existent information do not fit into a cohesive framework that can be used to predict time-dependent behavior under these varying conditions.

During press drying, perpendicular-to-grain strain (i.e., thickness loss) is a function of pressure, temperature, moisture content, and drying time. The temperature of the wood gradually increases and the moisture content gradually decreases (Fig. 1). The changes in temperature that take place simultaneously with changes in moisture content result in changes in thickness that cannot be predicted from simple shrinkage and thermal expansion data (Schniewind 1968). These changes also make mathematical analysis of rheological behavior so complicated that few models of practical value have been developed. A practical model requires simplifying the assumptions that are used to analyze the rheological characteristics.

DEVELOPMENT OF VISCOELASTIC MODEL

General viscoelastic model

Assume that a plate is compressed by the amount $\epsilon(t)$ per unit length by the applied average stress $\sigma(t)$. The strain $\epsilon(t)$ of linear viscoelastic materials can be
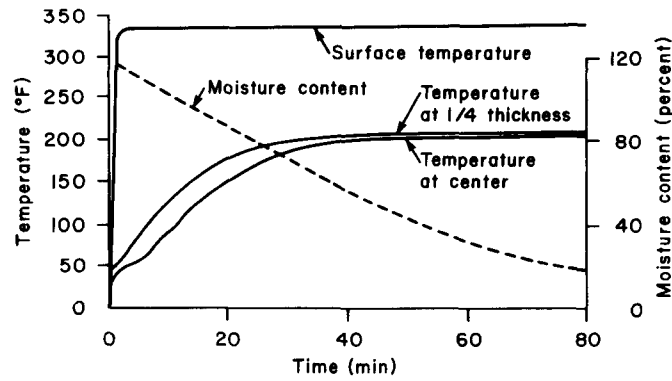
FIG. 1.   Changes in temperature and moisture content of 1.60-in.-thick loblolly pine during press drying at 25 lb/in.² and 350 F. (ML89 5650)

postulated to depend on the stress $\sigma(\tau)$ to which the material was subjected at all times τ up to and including time t. This can be expressed mathematically in the form (Lockett 1972)

$$\epsilon(t) = \int_{-\infty}^{t} \psi(t - \tau)\dot{\sigma}(\tau) \, d\tau \tag{1}$$

where $\dot{\sigma}(t) = \partial\sigma/\partial\tau$ and ψ represent the particular material response function. By transformation of variables and integration by parts, Eq. (1) can be written expressing $\epsilon(t)$ in terms of the stress history $\sigma(\tau)$ as

$$\epsilon(t) = \int_{-\infty}^{t} \phi(t - \tau)\sigma(\tau) \, d\tau \tag{2}$$

where ϕ is the creep function for the material, which must be obtained experimentally or from the physics of the material structure.

By using a semiempirical approach to material characterization, strain is a function of time and stress level in single-step creep tests, as expressed in the form (Lockett 1972)

$$\epsilon(\sigma, t) = a(\sigma) + b(\sigma)f(t). \tag{3}$$

The first term in Eq. (3) represents the instantaneous elastic component. The second term represents a viscoelastic contribution in which time and stress dependence are separable.

For complex-step creep tests where changes in temperature T and moisture content M occur, Eq. (3) can be written as

$$\epsilon(\sigma, T, M, t) = a(\sigma, T, M) + b(\sigma, T, M)f(t) \tag{4}$$

where the stress dependence of strain is a function of temperature. The assumption is made that the strain property of the material is affected by the absolute temperature of the material. The temperature is assumed to be constant during creep because in this experiment, it was not possible to monitor the complex variation of temperature with both position and time.

Although no particular problem arises in assuming the general dependence of the functions a, b, and f on their arguments, empirical representations have usually sought to model the functions through simple analytical expressions that involve only a few constant parameters. The time dependence can often be modeled adequately by a simple power law of the form (Lockett 1972)

$$f(t) = t^n \tag{5}$$

where n is a constant.

Under the specific conditions of this study, Eq. (5) may be as simple and accurate as functions that contain several exponential terms representing a number of retardation times. Therefore, Eq. (4) can be written in the form

$$\epsilon(\sigma, T, M, t) = a(\sigma, T, M) + b(\sigma, T, M)t^n. \tag{6}$$

If we divide a typical strain–time curve (not including creep recovery) into three parts (Fig. 2) according to either instantaneous or time-dependent strain, Eq. (2) can then be written in three parts:

$$\epsilon(t) = \int_{-\infty}^{0} \phi(t - \tau)\sigma(\tau)\,d\tau + \int_{0}^{t-\Delta t} \phi(t - \tau)\sigma(\tau)\,d\tau + \int_{t-\Delta t}^{t+\Delta t} \phi(t - \tau)\sigma(\tau)\,d\tau. \tag{7}$$

In Eq. (7), the first term represents the initial instantaneous strain after stress is applied, the second term time-dependent strain, and the third term final instantaneous elastic recovery after releasing the stress. (We assume Δt approaches zero compared to t.) Comparing Eq. (7) with Eq. (6), we can write the initial instantaneous component ϵ_1 (initial elastic deformation, assuming the applied stress is low enough that no plastic strain occurs) as

$$\epsilon_1 = \int_{-\infty}^{0} \phi(t - \tau)\sigma(\tau)\,d\tau = a_1(\sigma, T, M) \tag{8}$$

the time-dependent creep ϵ_2 as

$$\epsilon_2 = \int_{0}^{t-\Delta t} \phi(t - \tau)\sigma(\tau)\,d\tau = b(\sigma, T, M)t^n \tag{9}$$

and the final instantaneous component ϵ_3 (final elastic springback) as

$$\epsilon_3 = \int_{t-\Delta t}^{t+\Delta t} \phi(t - \tau)\sigma(\tau)\,d\tau = a_3(\sigma, T, M) \tag{10}$$

where $t \to 0$.

In press drying, stress σ is independent of time, so we can write Eqs. (8) to (10) as

$$\epsilon_1 = \int_{-\infty}^{0} \phi(t - \tau)\sigma(\tau)\,d\tau = \sigma^{m_1}a_1(T, M) \tag{11}$$

$$\epsilon_2 = \int_{0}^{t-\Delta t} \phi(t - \tau)\sigma(\tau)\,d\tau = \sigma^{m_2}b(T, M)t^n \tag{12}$$

$$\epsilon_3 = \int_{t-\Delta t}^{t+\Delta t} \phi(t - \tau)\sigma(\tau)\,d\tau = \sigma^{m_3}a_3(T, M) \tag{13}$$
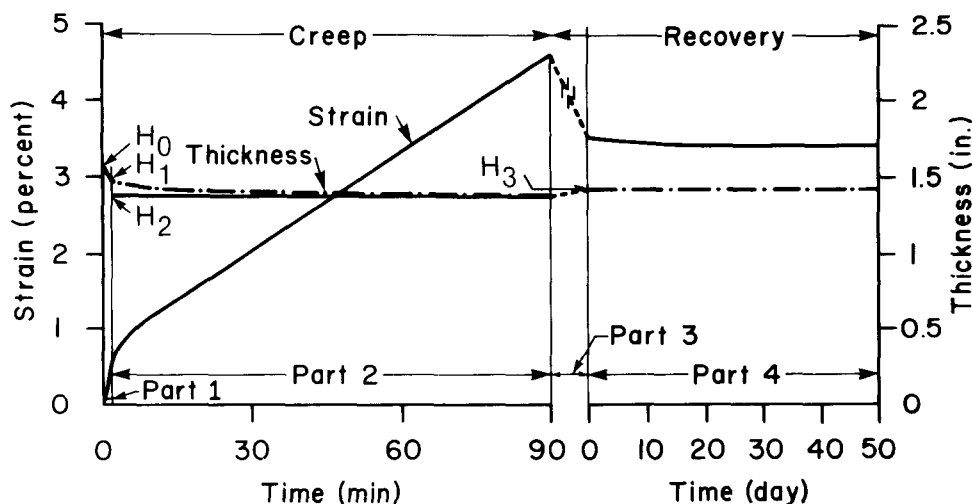
FIG. 2. Method of dividing strain–time press-drying curve into four parts: (1) initial elastic deformation, (2) viscoelastic deformation, (3) final elastic springback, and (4) creep recovery. Loblolly pine, 1.60-in. thick, 50 lb/in.², 350 F. (ML89 5649)

where m_1, m_2, and m_3 are constants that characterize the three different strain stages.

Thus, the creep function in press drying can be expressed as

$$\phi = b(T, M)t^n.$$

Studies have shown that creep is affected exponentially by temperature and moisture content (Schaffer 1972; Schniewind 1968). The rate of moisture change has been found to influence the rate of creep but not total creep, the latter generally being proportional to total change in moisture content (Schniewind 1968). Based on these studies, we can write the function b as

$$b(T, M) = A \cdot \exp(-Q/RT' + C\Delta M)$$
$$= A \cdot \exp(-D'/T + C\Delta M). \tag{14}$$

Therefore, total creep can be modeled as

$$\epsilon_2 = \int_0^{t-\Delta t} \phi(t - \tau)\sigma(\tau) \, d\tau$$
$$= \sigma^{m_2} t^n b(T, M)$$
$$= A \cdot \exp(-D'/T + C\Delta M) \cdot \sigma^{m_2} \cdot t^n \tag{15}$$

where A, C, and D' are material constants, Q is average energy of activation for position changes of molecular segments, R the gas constant, T' temperature in kelvins, T temperature in degrees Fahrenheit, and ΔM total moisture content change during creep.

In press drying, the initial moisture content of wood is much higher than the fiber saturation point, and it is considered a constant in terms of affecting total creep. If we assume the fiber saturation point is constant and no dimensional change occurs when the moisture content is above the fiber saturation point, then ΔM depends only on the final moisture content of the wood. Final moisture content

depends on the temperature and drying time (Simpson and Tang 1988) according to the following relationship:

$$M_f = \left(W_0 - \sqrt{\frac{2kV_0(W_0 - W_d)(T_s - T_c)t}{Q'(L/2)^n}} \right) \Big/ W_d \qquad (16)$$

where

M_f = final moisture content
W_0 = green weight
W_d = ovendry weight
k = thermal conductivity of dry wood
V_0 = green volume
T_s = surface temperature of wood
T_c = temperature at center of wood
Q' = latent heat of vaporization of water
L = thickness
n = thickness exponent.

Therefore, we assume that ΔM is not an independent variable in the model of creep relating to press drying.

We also assume that the temperature of wood in press drying either rapidly reaches the platen temperature or we assume an average temperature throughout the drying period; that is, we assume that temperature is not a time-dependent variable in the model. According to Eqs. (15) and (16), we can express the time-dependent part of the model, Eq. (12), in the form

$$\epsilon_2 = \int_0^{t-\Delta t} \phi(t - \tau)\sigma(\tau) \, d\tau = \sigma^{m_2}(T, M)t^n = A\sigma^{m_2}\exp(-D'/T + C\Delta M)t^n$$

and since

$$\Delta M = f(M_f) = f(T, t), \quad \epsilon_2 = A\sigma^{m_2}\exp(-D/T)t^n \qquad (17)$$

where D is a constant.

The time-dependent recovery (Fig. 2, part 4) is considered as the reverse of time-dependent creep and can be described by the same equation as time-dependent creep (Wang 1987; Youngs 1957). Thus, Eq. (12) can be extended to express the recovery creep

$$\epsilon_4 = \int_t^{+\infty} \phi(t - \tau)\sigma(\tau) \, d\tau = -\sigma^{m_4}b_4(T, M)t^{n_4}$$

where m_4 and n_4 are constants.

However, function b_4 will be affected by both previous physical characteristics of the material under stress and the new environment where the material will be placed after releasing stress.

Application of model to press drying

Figure 2 shows a typical strain-time curve during press drying. Considering each variable (pressure, temperature, and drying time) as having a different effect on the strain–time characteristics of different stages of press drying, we divided

the whole curve into four parts: (1) initial elastic deformation, (2) viscoelastic deformation, (3) final elastic springback, and (4) creep recovery.

Initial elastic deformation (ϵ_1).—In the first minute of press drying (Fig. 2, part 1), the wood temperature and moisture content do not change significantly. If the applied stress is low, only elastic deformation occurs (Youngs 1957). Therefore, strain is proportional only to the pressure p. Eq. (11) can be written in the following form:

$$\epsilon_1 = Bp^{m_1} \tag{18}$$

where B and m_1 are material constants that can be estimated with experimental data and regression analysis.

Viscoelastic deformation (ϵ_2).—In part 2 of Fig. 2, wood temperature increases and moisture content decreases. Pressure, temperature, and moisture content change will significantly affect creep. Because moisture content change directly relates to the drying time and temperature, Eq. (17) can be used to describe the creep curve

$$\epsilon_2 = A_2 p^{m_2} \exp(-D_1/T)t^n \tag{19}$$

where A_2, m_2, D_1, and n are material constants that can be estimated with experimental data and regression analysis.

Final elastic springback (ϵ_3).—After releasing the pressure, elastic springback will occur immediately. In part 3 of Fig. 2, the temperature of the wood is almost the same as the platen temperature, and final moisture content is below the fiber saturation point. Temperature and moisture content are known to affect the modulus of elasticity of wood. Previous studies have established that a decrease in the relaxation modulus occurs as temperature and moisture content increase (Schniewind 1968). In press drying, final moisture content is directly related to total drying time and drying temperature. Therefore, drying time and temperature can be used to model the final elastic springback instead of final moisture content because total drying time can be measured more easily than final moisture content. Therefore, the final elastic springback can be modeled from Eq. (13). Knowing that the modulus of elasticity of wood is proportional to temperature T and final moisture content M_f, we can model the function $a_3(T, M_f)$ as

$$\epsilon_3 = \sigma^{m_3} A_3 \exp(-D'_2/T + E'M_f)$$

where m_3, A_3, D'_2, and E' are material constants.

From Eq. (16), we know that $M_f = f(T, t)$. Therefore,

$$\epsilon_3 = A_3 \exp(-D_2/T + Et)p^{m_3}. \tag{20}$$

Creep recovery.—As will be described later, measurement of creep recovery (Fig. 2, part 4) was confounded by moisture content changes. Thus, no attempt was made to model this part of the creep recovery curve. Alternate tests that give some insight into the recovery will be described later.

The first three parts of the thickness strain can also be described as

$$\epsilon = \frac{H_0 - H_3}{H_0} = 1 - \frac{H_3}{H_0}$$

where H_0 is original thickness and H_3 thickness immediately after release of pressure (Fig. 2). Here

$$\epsilon_1 = \frac{H_0 - H_1}{H_0} \quad \text{or} \quad H_1 = H_0(1 - \epsilon_1)$$

$$\epsilon_2 = \frac{H_1 - H_2}{H_1} \quad \text{or} \quad H_2 = H_1(1 - \epsilon_2)$$

where H_1 is thickness immediately after application of pressure and H_2 thickness after drying while specimen is still under pressure.

Because $H_2 < H_3$,

$$\epsilon_3 = \frac{H_3 - H_2}{H_2} \quad \text{or} \quad H_3 = H_2(1 + \epsilon_3)$$

Therefore

$$\epsilon = 1 - (1 - \epsilon_1)(1 - \epsilon_2)(1 + \epsilon_3). \tag{21}$$

EXPERIMENTAL

Materials and apparatus

Green loblolly pine 2 by 4's were obtained from 35-year-old plantation trees in Arkansas. The trees had small-end diameters ranging from 8 to 14 in., and the 2 by 4's were 8 ft long. Thirty 2 by 4's were each cut into three 32-in.-long specimens and then surfaced to 1.60 in. thick. Specimens were randomly assigned to 10 test runs: nine for press drying and one for comparison with air drying. Nine specimens were assigned to each test run. All specimens were coded for identification through the processing and testing, and they were end-coated twice with a heavily pigmented aluminum paint before drying to reduce moisture loss from the ends of the boards. Specimens were stored in the cold to prevent drying and biological deterioration.

All press drying tests were conducted in a 3- by 3-ft oil-heated press with microcomputer control and a data recording system. Thickness measurements and recording instruments were sensitive to changes of 0.001 in.

Testing methods and procedure

The investigation was designed to include the creep and recovery in compression perpendicular to the grain at three levels of temperature—350 F, 415 F, and 475 F; three levels of pressure—25, 50, and 75 $lb/in.^2$; and one drying time at each drying condition. There were nine replicates, which is the capacity of each press load, at each of the experimental conditions.

Before press drying, specimens were warmed to room temperature in plastic bags. Two thickness measurements, 8 in. from each end, were taken on each specimen for the initial thickness under no pressure. Specimens were weighed before being placed into the press.

Three thermocouples were placed inside some specimens to measure the temperature changes at the center, one-quarter thickness, and surface of the boards. The temperatures of three specimens were measured during each press run. During

TABLE 1.   *Coefficients of nonlinear regression of initial elastic deformation* (ϵ_i).

	ln ϵ_i = ln B + $m_i$ln p		
Parameter	Estimated value	Standard error	F value (R value)
ln B	−1.3879	0.3293	43.15 (0.937)
m_1	0.5723	0.0871	

press drying, the temperature, pressure, drying time, and thickness changes were automatically recorded.

Immediately after releasing pressure, thickness was measured in two places on each board to obtain the instantaneous thickness springback. Specimens were then weighed to estimate final moisture content.

To measure the time-dependent thickness recovery of press-dried boards at room temperature, thickness was measured periodically for 2 months during storage at 70 F and 4% equilibrium moisture content. Unfortunately, no significant thickness recovery was found because the moisture content of the specimens also changed during this time. After the 2-month recovery period, some specimens were oven-dried and then placed in a conditioning room at 80 F and 20% equilibrium moisture content for 2 more months to compare the creep recoveries when all specimens were experiencing the same moisture content change. We compared specimens dried at four pressure levels—0 (air dried), 25, 50, and 75 lb/in.^{2}.

RESULTS AND DISCUSSION

As described in the previous section, the strain-time curve of wood during press drying was divided into four parts according to the individual strain characteristics as related to temperature, pressure, drying time, and moisture content. The different models were developed to describe the various parts of the strain-time curve.

Initial elastic deformation (ϵ_i)

Initial elastic strain was related only to pressure because the moisture content and temperature of the wood were assumed constant in the first minute of press drying. Equation (18) was used to describe the strain behavior. Because the average initial moisture content of the specimens was over 100%, much higher than the

TABLE 2.   *Comparison of model and experimental values of initial elastic deformation* (ϵ_i).

	ln ϵ_i = ln B + $m_i$ln p = −1.3879 + 0.5723 ln p		
		ϵ_i value (percent)	
Group number	Pressure (lb/in.^{2})	Observed	Predicted
12A	25	1.68	1.58
15A	25	1.68	1.58
18B	25	1.56	1.58
16C	50	1.97	2.34
22A	50	2.12	2.34
22B	50	2.23	2.34
21A	75	3.24	2.95
21B	75	3.30	2.95

TABLE 3.   *Results of nonlinear regression of viscoelastic deformation* (ϵ_2).

	$\epsilon_2 = A_2 p^{m_2} \exp(-D_1/T) t^n$		
Parameter	Estimated value	Standard error	F value
A_2	0.046	0.00708	2,421.7
m_2	0.719	0.0308	
D_1	491.30	41.767	
n	0.712	0.0232	

fiber saturation point of wood where moisture content begins to affect mechanical properties, we considered strain to be independent of green moisture content.

The results of the nonlinear regression analysis of Eq. (18) and comparison of the model with experimental data are shown in Tables 1 and 2. The model fit the experimental data reasonably well. As one would expect, the elastic strain increased with pressure. Plasticizing and collapsing of the cell wall probably did not occur because of the low pressure and temperature, thus resulting in only elastic deformation in the first minute. The third set of specimens tested at 75 lb/in.^{2} (Table 2) contained an uncharacteristically large number of knots, and we decided not to include these data in the analysis.

Viscoelastic deformation (ϵ_2)

The time-dependent strain, both recoverable and irrecoverable, took place in part 2. The viscoelastic behavior during press drying is described by Eq. (19). The results of the nonlinear regression analysis of Eq. (19) are presented in Table 3 and Figs. 3 to 5. The model agreed well with the experimental data within the limits of the three levels of pressure (25, 50, 75 lb/in.^{2}) and temperature (350 F, 415 F, 475 F). The model and experiments indicated that total creep was significantly affected by pressure, temperature, and drying time. The total creep was proportional to exponential terms of pressure, temperature, and drying time. Pressure was the most significant factor in determining total time-dependent deformation, but temperature also played an important role in affecting total creep.

Typical creep curves of many materials approach an asymptote in strain at long times. However, the strain of wood in press drying increases constantly within the time frame of the experiment. This indicates that the strain that occurred within the drying time was only a part (initial or middle period) of the total of a typical creep curve. Within this initial or middle period of total creep, drying time significantly affected total creep strain. In press drying, high pressure, long drying time, and high temperature all increase thickness loss caused by creep.

Figures 3 to 5 show a difference in model and experimental creep values. One reason may be that we did not consider the average density of wood as one of the variables affecting the total creep in the model. Another possible reason is that the value of n in Eq. (19) is not constant at different levels of temperature and moisture content. Youngs (1957) showed that the value of n appears to be independent of stress but is not independent of either temperature or moisture content. Unfortunately, the relationship between n, temperature, and moisture content could not be determined from our experiment. Another possible reason is the assumption in the model that temperature does not change with time under pressure. However, we know that temperature is really a function of both time
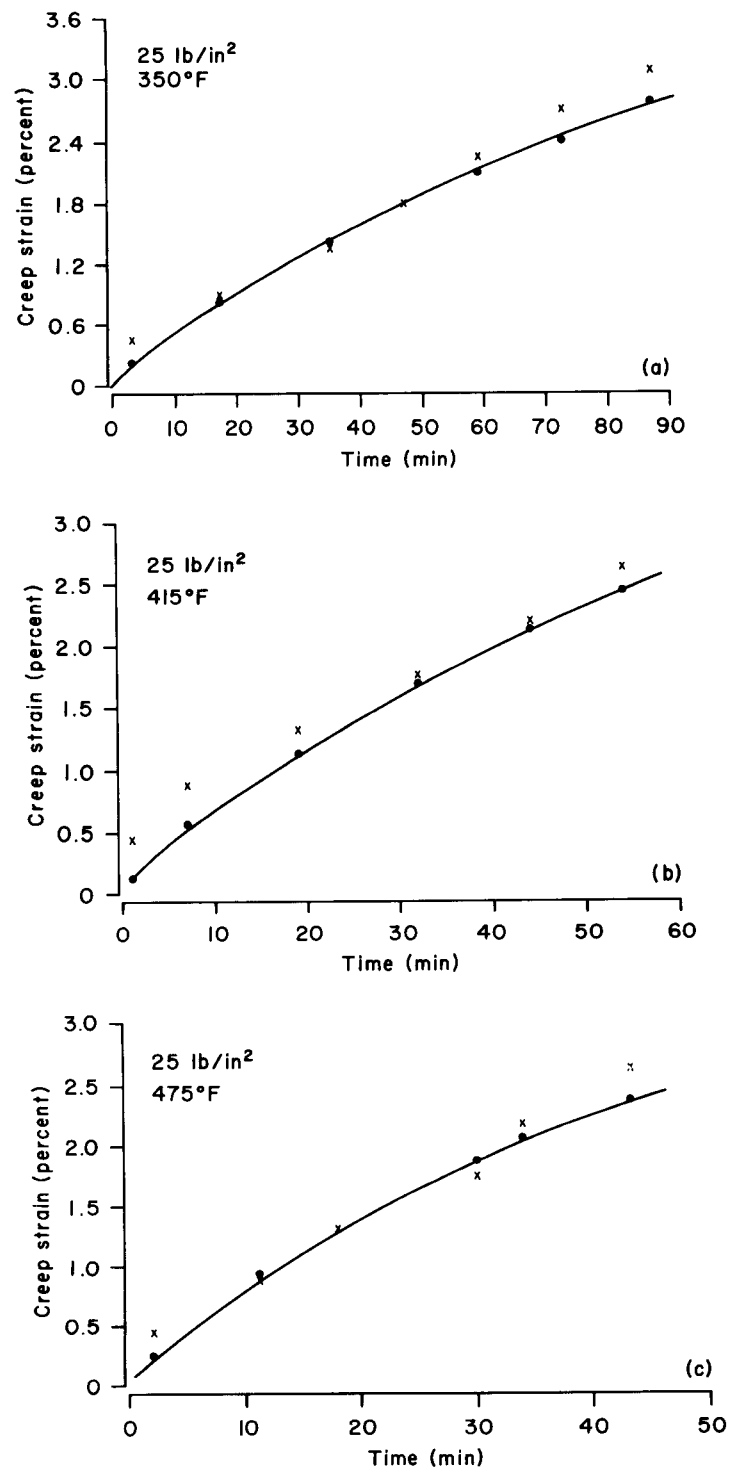
Fig. 3.   Predicted and observed (x) creep in press drying at 25 lb/in.² and various temperatures over time. (a) 350 F, (b) 415 F, (c) 475 F. (ML89 5648)
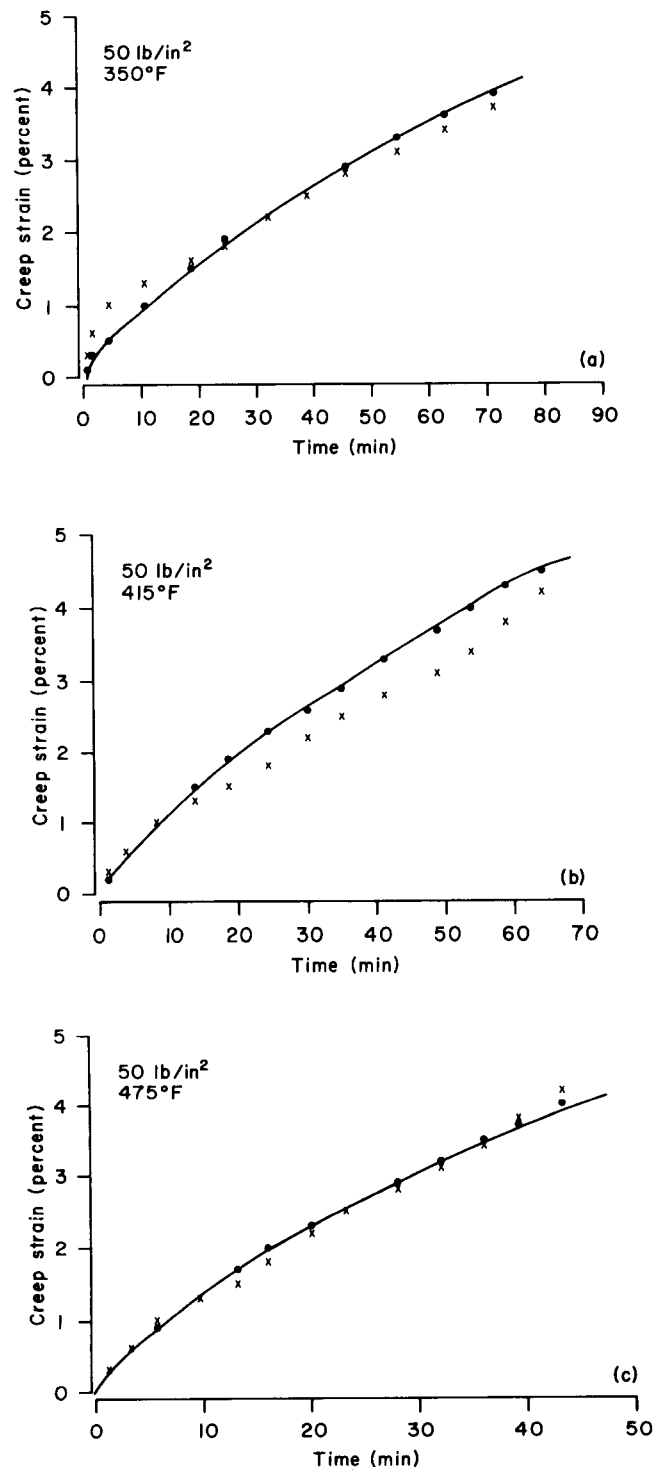
FIG. 4. Predicted and observed (x) creep in press drying at 50 lb/in.^{2} and various temperatures over time. (a) 350 F, (b) 415 F, (c) 475 F. (ML89 5645–7)
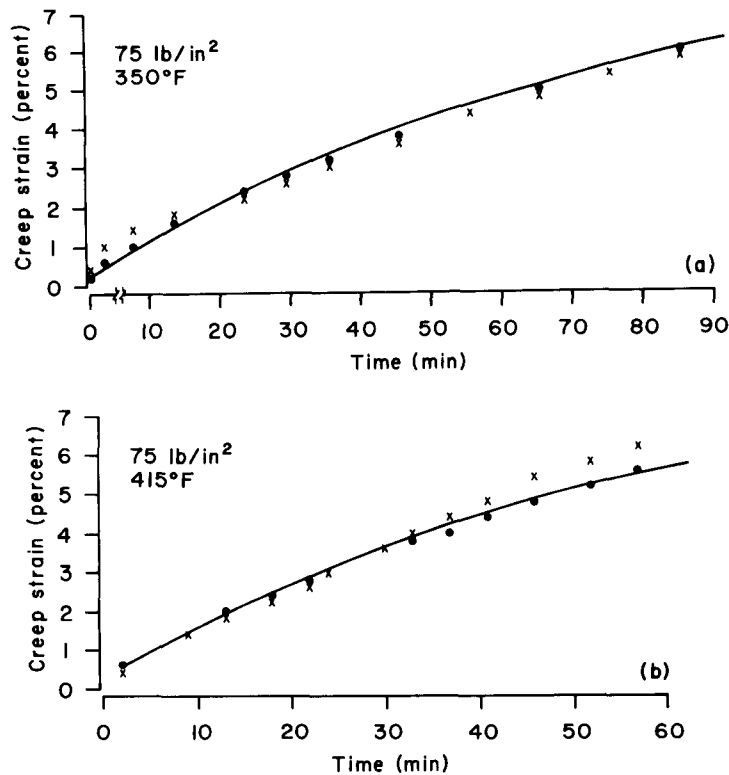
FIG. 5. Predicted and observed (x) creep in press drying at 75 lb/in.^{2} and various temperatures over time. (a) 350 F, (b) 415 F. (ML89 5643–4)

(heat-up from ambient temperature) and distance between surface and center of wood (Simpson et al. 1988).

Final elastic springback (ϵ_s)

Final elastic springback should be related only to pressure, wood temperature, and total drying time, and it can be expressed by Eq. (20). The nonlinear regression results listed in Tables 4 and 5 show that the model fit the experimental data at the three levels of pressure and temperature. However, considerable standard errors occurred for some coefficients (Table 3), possibly because of the small number of tests.

The results indicated that the final instantaneous elastic springback can be related exponentially to pressure, temperature, and total drying time. Pressure appeared to be the major factor in determining total elastic springback, but it is uncertain whether temperature or drying time had the greatest influence on elastic springback. We expected that elastic springback would be negatively proportional to the total drying time because the initial relaxation modulus decreases as the moisture content increases (Schniewind 1968) and because in press drying, the increase in total drying time results in a decrease in final moisture content. However, that the elastic springback was negatively proportional to wood temperature does not agree with the previous studies on stress relaxation (Schniewind 1968).

TABLE 4. *Coefficients of nonlinear regression of final elastic springback* (ϵ_3).

$\epsilon_3 = 0.0246 \exp(1{,}534.9/T - 0.0301t)p^{0.8166}$			
Parameter	Estimated value	Standard error	F value
A_3	0.0246	0.0262	325.2
D_2	-1,534.9	609.0	
E	-0.0301	0.0118	
M_3	0.8166	0.1072	

One possible explanation for this disagreement is that the instantaneous elastic springback is not within the concept of stress relaxation. Another explanation is that high temperature and pressure during a long drying time may plasticize the wood components so that springback strain decreases as drying temperature increases.

Final elastic springback can be considered the reverse of initial elastic compression. However, total elastic strain values were quite different because wood temperature, moisture content, and cell structure were changed during press drying. As a result, the pressure, temperature, moisture content, and total drying time determined the elastic strain in the final elastic springback instead of only pressure and moisture content as in the initial elastic compression.

Time-dependent creep recovery

As previously mentioned, time-dependent thickness recovery was not significant after the specimens were unloaded and placed in storage at 70 F and 4% equilibrium moisture content for 2 months. The creep recovery was probably counteracted by shrinkage because the equilibrium moisture content in the conditioning room was lower than the final moisture content after press drying.

To investigate creep recovery behavior at different pressure levels, the specimens were oven-dried and conditioned as described in Experimental Procedure. The results of creep recovery tests in adsorption are presented in Fig. 6. Recoverable and irrecoverable creep values for each pressure level are listed in Table 6. Figure 6 shows that thickness recovery in adsorption was a function of the pressure applied during press drying. The recovered creep increased with pressure. Both recoverable and irrecoverable creep appeared to increase with an increase in pressure, but both types of creep were comparatively low in press drying because of the low pressures. Youngs (1957) observed that irrecoverable creep increased with stress and temperature at the same moisture content.

TABLE 5. *Comparison of model and experimental values of final elastic springback* (ϵ_3).

Group number	Pressure (lb/in.^{2})	Temperature (F)	Total drying time (min)	ϵ_3 value (percent)	
				Observed	Predicted
12A	25	350	80	2.47	2.46
15A	25	415	55	2.66	2.63
18B	25	475	50	2.14	1.92
16C	50	350	90	2.87	3.21
22A	50	415	65	3.32	3.43
22B	50	475	50	3.39	3.38
21A	75	350	90	4.78	4.47
21B	75	415	65	4.67	4.77

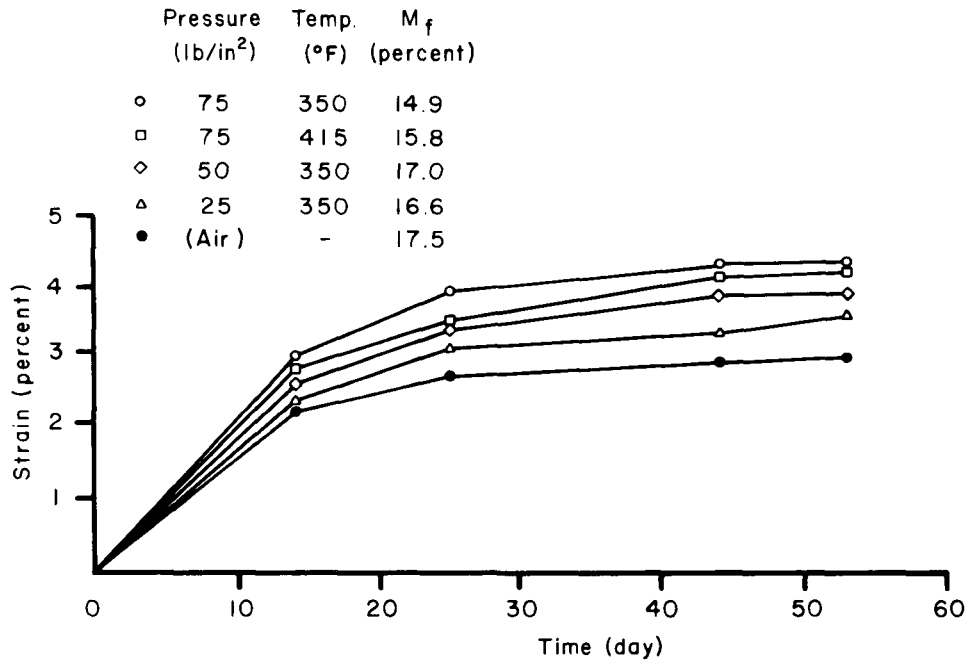| Pressure (lb/in^2)	Temp. (°F)	M$_f$ (percent)
o 75	350	14.9
□ 75	415	15.8
◇ 50	350	17.0
△ 25	350	16.6
● (Air)	–	17.5

FIG. 6.   Creep recovery of press-dried compared to air-dried loblolly pine over time. Several levels of pressure and two temperatures (350 F and 415 F) compared. M_f, final moisture content. Strain values based on oven-dry thickness of wood. Equilibrium moisture content of conditioning room was 20%. (ML89 5642)

Practical use of model

As a practical example of how the model might be used, consider a processing decision where nominal 2 by 4 loblolly pine will be press dried at 25 lb/in.^{2} platen pressure. A required decision might be whether to dry at 350 F or 475 F. If we assume an actual thickness of 1.75 in., about 110 min will be required to dry the wood from 120 to 15% moisture content at 350 F, but only about 65 min at 475 F (Simpson and Tang 1988). The shorter drying time is desirable, although the additional press capabilities required to reach 475 F must also be considered. We must also consider thickness loss. Excessive thickness loss decreases yield because of the larger green target thickness required from the sawmill. Using the model, we can estimate thickness loss for these two possible drying conditions. Time-dependent recovery will be ignored in this example because it appears to be small

TABLE 6.   *Results of recoverable and irrecoverable creep of loblolly pine wood in press drying.*

Group number	Pressure (lb/in.^{2})	Temperature (F)	Creep[a] Recoverable	Irrecoverable
19B	25	350	0.65	1.37
19C	50	350	0.87	1.50
21A	75	350	1.32	2.31
21B	75	415	1.19	2.74

[a] Creep based on ovendry thickness, not including normal shrinkage of the specimen. Specimens were stored under dry-bulb conditions at 80 F and 20% equilibrium moisture content for 2 months.
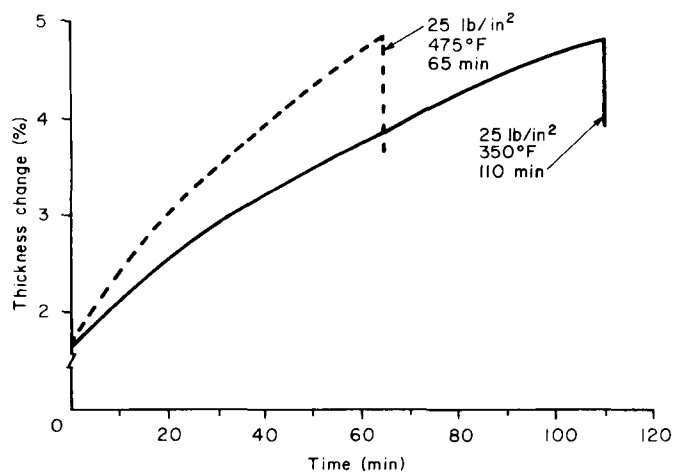
FIG. 7. Thickness change of 1.75-in.-thick loblolly pine during press drying. (ML89 5569)

within the time needed to process and ship lumber, and we were not able to model it. The results of the model predictions are shown in Fig. 7, where we can see that the model predicts nearly the same thickness loss for both drying conditions. Thus, the decision of which drying temperature to use can be simplified because thickness loss is the same.

CONCLUSIONS

The thickness change that occurs during press drying can be divided into four parts—initial elastic thickness loss upon application of pressure, viscoelastic thickness loss that continues throughout press drying, elastic springback upon release of pressure, and viscoelastic recovery that continues for some time after pressure release. The first three thickness changes can be modeled semiempirically from viscoelastic theory, resulting in a model and regression coefficients that can predict thickness changes reasonably well. Platen pressure, drying temperature, and drying time are the three independent variables in the model, and they all increase the change in thickness.

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